Sensor Development and Radiometric Correction for Agricultural Applications

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Abstract

This review addresses the challenges and progress in sensor development and radiometric correction for agricultural applications with particular emphasis on activities within the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS). Examples of sensor development include on-site development of sensors and platforms, participation in cooperative research and development agreements (CRADA) with commercial companies, and membership on NASA science teams. Examples of progress made in sensor radiometric correction suitable for agriculture are presented for both laboratory and field environments. The direction of future sensor development includes integrated sensors and systems, sensor standardization, and new sensor technologies measuring fluorescence and soil electrical conductivity, and utilizing LIght Detection and Ranging (lidar), hyperspectral, and multiband thermal wavelengths. The upcoming challenges include definition of the core spectral regions for agriculture and the sensor specifications for a dedicated, orbiting agricultural sensor, determination of an operational approach for reflectance and temperature retrieval, and enhanced communication between image providers, research scientists, and users. This review concludes with a number of avenues through which USDA could promote sensor development and radiometric correction for agricultural applications. These include developing a network of large permanent calibration targets at USDA ARS locations; investing in new technologies; pooling resources to support large-scale field experiments; determining ARS-wide standards for sensor development, calibration, and deployment; and funding interagency agreements to achieve common goals.

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Introduction

Spectral measurements in visible, near-infrared (NIR), thermal-infrared (TIR), and microwave wavelengths have been related to plant biomass, crop water stress, nitrogen deficiency, crop stand density, soil moisture, weed and insect infestations, and many other field conditions (e.g., Hatfield and Pinter, 1993). These theoretical and empirical algorithms have the potential to provide needed biophysical information to farm and ranch managers in a timely, economical manner. This potential will only be realized when sensors and radiometric corrections are optimized for agriculture.

Sensor development for agriculture is driven largely by stringent sensor resolution and operation specifications unique to farm management applications. Such specifications might include a 2- to 5-m spatial resolution with a one- to three-day revisit period, 1-pixel geolocation accuracy, 24-hour product delivery time, and routine production of atmospherically corrected products (Moran, 2000). At this time, several satellite-based sensors can meet some of these specifications. Unfortunately, no single satellite system can provide fine resolution images globally on a

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frequent basis. Tractor-based systems can, however, easily meet the required specifications at the field scale, and, in fact, are currently deployed by some innovative farmers. Thus, sensor design for agriculture has many options for platform size and complexity ranging from yokes, booms, irrigation pivots, tractors, and small aircraft, to jet aircraft, high altitude powered platforms (HAPP), military aircraft, and satellites. The diverse agricultural applications of remote sensing and the multitude of possible platforms have led to a great variety of sensors for which agriculture is identified as the prime user.

The requirements for sensor radiometric calibration and atmospherically corrected products for agriculture are equally stringent. Again, farm management applications are setting the standard. Agricultural algorithms for determining stand density, nitrogen deficiency, and other field conditions are often based on small changes of visible and NIR reflectances or surface temperature. This, combined with the fact that agricultural targets are characterized by extremely low reflectance in the visible wavelengths (~0.02 reflectance in the red waveband for mature irrigated crops), has resulted in a suggested uncertainty for reflectance measurements of ±0.01 (Pinter *et al.*, 1990) and temperature measurements of 1°C (Kimball *et al.*, 1999).

This accuracy requirement is not currently being met by orbiting sensors despite significant advances in radiometric calibration and the fact that the latest land-observation satellites carry on-board radiometric reference sources. These sensors have radiometric uncertainty within 5 percent. However, radiometric calibration is only the first step toward optical wavelength surface reflectance products. The second step is atmospheric correction. The NASA Terra MODerate-resolution Imaging Spectroradiometer (MODIS) surface reflectance product represents a first attempt at routinely producing an atmospherically corrected product for land surfaces. The product accuracy as tested with Landsat Thematic Mapper (TM) was estimated to be ±0.015 absolute reflectance for visible channels and ±0.03 for the shortwave infrared (SWIR) region (Ouaidrari and Vermote, 1999). The Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) in-flight accuracy requirement for temperature ranges from 1 to 3 K, depending on the target temperatures (Fujisada, 1998), and the retrieval of surface temperature from Landsat Enhanced Thematic Mapper Plus (ETM+) band 6 has been estimated to be within 1.5°C (Schott *et al.*, 2001).

Sensors on small platforms can minimize atmospheric attenuation by making measurements below the bulk of the atmosphere. Without the burden of in-flight sensor calibration and post-flight atmospheric correction, reflectance measurements can be made to within ±0.01 absolute reflectance in the visible and NIR wavelengths (Slater *et al.*, 1986), and surface temperature can be measured to within ±1°C (Perry and Moran, 1994).

Researchers of the USDA Agricultural Research Service (ARS) recognized the value of sensor and radiometric calibration to agricultural remote sensing applications very early. Many standard calibration procedures, such as those for hand-held radiometric instruments, were outlined by ARS researchers in landmark publications (e.g., Jackson *et al.*, 1980). These publications and proposed procedures were quickly adopted by the remote sensing research community, thus resulting in an increased awareness of the importance of sensor technology and calibration issues. More examples of sensor and radiometric correction developments are presented in the following subsections with emphasis on the progress made by ARS. Suggestions for research direction for the next ten years are offered, followed by a discussion of expected challenges and solutions.

Current and Historic Activities

Sensor Development

Historically, the ARS has used three avenues for sensor development–on-site development of sensors and sensor platforms, participation in cooperative research and development agreements (CRADA), and membership on NASA science teams for development of sensors aboard satellites.

On-Site Sensor Development

The infrared thermometer (IRT) is a good example of on-site sensor development that started with prototypes at ARS locations and that has now mushroomed into a viable business. USDA scientists long ago recognized that a direct measurement of some plant parameter would be superior to measurement of water status of the soil for monitoring the plant's response to its atmospheric and edaphic environment (see review by Jackson (1982)). In the 1960s, scientists began using crude infrared thermometers (Figure 1) to remotely sense leaf temperatures (for a discussion of basic IR radiation thermometry, see Fuchs and Tanner (1966)). Wiegand and Namken (1966) thus observed that cotton-leaf temperatures increased linearly with increasing insolation, and decreased linearly with increasing turgidity of the leaves. Based on these observations, a measurement protocol was suggested that is still in use today: leaf temperature interpretation requires simultaneously measured radiation data, and the early afternoon is a good time of day for making leaf temperature measurements.

With the commercial development of the IRT, research moved from studies of individual leaves to investigations of entire crop canopies and development of indices to be used for field management activities such as irrigation scheduling and monitoring general plant ecosystem health. Three simple algorithms, Stress Degree Day (SDD), Canopy Temperature Variability (CTV), and Temperature Stress Day (TSD), were the foundation for subsequent, more complex stress indices, including the Crop Water Stress Index (CWSI) and the Thermal Kinetic Window (TKW), which are now well documented and commercially accepted (Table 1).

Figure 1. Prototype infrared thermometer (IRT) used for early studies in crop water stress at the U.S. Water Conservation Laboratory.

TABLE 1. SOME CROP INDICES DERIVED FROM IRT MEASUREMENTS

Index Name	General Description	Citation
Stress Degree Day (SDD)	Related to water use. Used to schedule crop irrigations and monitor grassland stress	Idso *et al.*, 1981; Jackson *et al.*, 1977
Canopy Temperature Variability (CTV)	Linked to the onset of plant stress, which was signaled when CTV exceeded a threshold value	Clawson and Blad, 1982
Temperature Stress Day (TSD)	Used to signal the need for irrigation and to predict the phenologic development of crops	Gardner *et al.*, 1981a; Gardner *et al.*, 1981b
Crop Water Stress Index (CWSI)	Closely related to soil moisture content, soil salinity, soil waterlogging, plant water potential, leaf diffusion resistance, and photosynthesis	Jackson *et al.*, 1981; Idso, 1982; Jackson, 1987
Thermal Kinetic Window (TKW)	TKW links the biochemical characteristics of a plant with its optimal leaf temperature range for irrigation management applications	Burke *et al.*, 1988

These are examples of symbiotic relations in which thermal sensor development influenced algorithm development and vice versa to expand the science of remote sensing for agricultural application. Similar examples could be cited in the development of sensors to measure surface reflectance. With the absence of an orbiting sensor system dedicated to the needs of agricultural management, scientists at the ARS location in Weslaco, Texas, developed state-of-the-art, multispectral digital video imaging systems (Everitt *et al.*, 1995; Escobar *et al.*, 1997; Everitt *et al.*, 1997a). The choice of a video system was influenced by the fact that video offered near-instant availability of imagery for visual assessment, immediate potential for digital processing of the electronic signal, and higher light sensitivity than film cameras, permitting imaging in narrow spectral bands. Video equipment is also inexpensive, portable, and easy to use. For example, Weslaco scientists assembled a digital video imaging system with visible, NIR, and SWIR sensitivity. This system produces imagery similar to Landsat TM bands 5, 4, and 3. Another system developed at Weslaco (Escobar *et al.*, 1998) is the Airborne Digital Video Imaging Systems (ADVIS) comprised of 12 charge-coupled-device (CCD) analog video cameras and a computer equipped with a single multichannel digitizing board (Figure 2). The system cameras are equipped with various narrowband interference filters to acquire images within the visible/NIR (400- to 1000-nm) spectral waveband. The system is unique because the real-time color composite imagery it provides is of adequate quality for assessing scenes of interest, and there is no need for post-processing band registrations. The development of this system and frequent deployment on ARS-owned aircraft allowed the Weslaco scientists to demonstrate theoretical and practical use of remote sensing for agricultural and natural resources management. Applications have included discrimination of plant communities/species and soil surface conditions (Everitt *et al.*, 1997a; Everitt *et al.*, 1997b; Escobar *et al.*, 2000), detection of pest infestations (weeds and insects) (Everitt *et al.*, 1997b; Everitt *et al.*, 1999), and assessing water quality (Webster *et al.*, 2000).

Similarly, scientists at the ARS location in Shafter, California, worked with private companies to assemble the Shafter Airborne Multispectral Remote Sensing System (SAMRSS; Figure 3). SAMRSS consists of three identical 1024- by 1024-pixel, 12-bit Dalsa cameras and one Merlin Uncooled Bolometer thermal camera (8 to 14 μm) along with two computers for camera control and image acquisition mounted in an aluminum housing designed to fit into a standard Leica aircraft survey camera mount. Each of the Dalsa cameras sits on a specially built mount designed and built by ARS personnel that allows precise alignment of the cameras. Narrow bandpass filters (10-nm visible, 40-nm NIR) allow acquisition of images centered at 550 nm, 660 nm, and 850 nm. SAMRSS has been deployed in Shafter research for the early detection of spider mites in cotton (Fitzgerald *et al.*, 1999) and estimation of cotton canopy temperature for incomplete canopies (Maas *et al.*, 2000). Results indicate

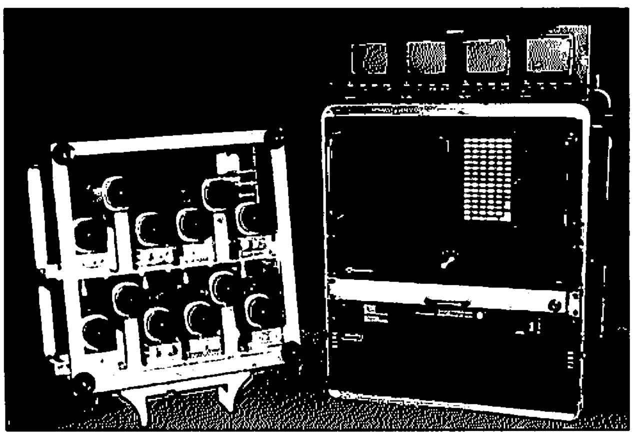

Figure 2. The airborne digital video imaging systems (ADVIS) developed at Weslaco, Texas.

Figure 3. The Shafter Airborne Multispectral Remote Sensing System (SAMRSS).

that, through the use of computer enhancement and digital processing, spider mite damage can be detected early in the season and distinguished from other types of image anomalies such as water stress. It also is being used as the principal instrument for image acquisition for precision agricultural as part of the USDA-ARS and NASA Ag20/20 project.

Other ARS efforts in sensor development have focused on the use of narrow spectral bands (Blackmer *et al.*, 1995; Blackmer *et al.*, 1996) and use of the "red edge" (Bausch *et al.*, 1998; Barnes *et al.*, 2000) for crop nitrogen application. In each case, the prototype sensor has been developed in collaboration with ARS scientists, and the first prototype has been tested on-site at the ARS location.

On-Site Sensor Platform Development

The USDA has been involved in development of innovative sensor platforms suitable for agricultural applications. Scientists at the ARS Water Management Research Center in Ft. Collins, Colorado, developed a boom-type data acquisition system mounted on a high-clearance tractor to measure crop canopy radiance and incoming irradiance (Figure 4). This system is a modification of the one described by Bausch *et al.* (1990) and consists of two instrument platforms with four-band radiometers. One instrument platform is attached to the boom; the other is mounted on the tractor's roll-over protection system (ROPS). The down-looking radiometer (on boom) measures target radiance with 15° field of view (FOV) perpendicular to the crop surface and the other radiometer (on the tractor ROPS) looks upward to measure irradiance with an FOV of 180°. Bidirectional reflectance of the target is calculated for each waveband based on an intercalibration of the up-looking radiometer and the target-viewing radiometer with respect to a calibrated $BaSO_4$ panel. The sensor system has been used to develop and evaluate reflectance-based crop coefficients for corn (Neale *et al.*, 1989; Bausch, 1995) and nitrogen deficiency assessment in corn (Bausch and Duke, 1996; Bausch and Diker, 2001). Similarly, at the ARS Jornada Experimental Range in Las Cruces, New Mexico, a 30-m extendable boom was used to position instruments at various elevations above the surface to sample various vegetation component signatures (Privette *et al.*, 2000).

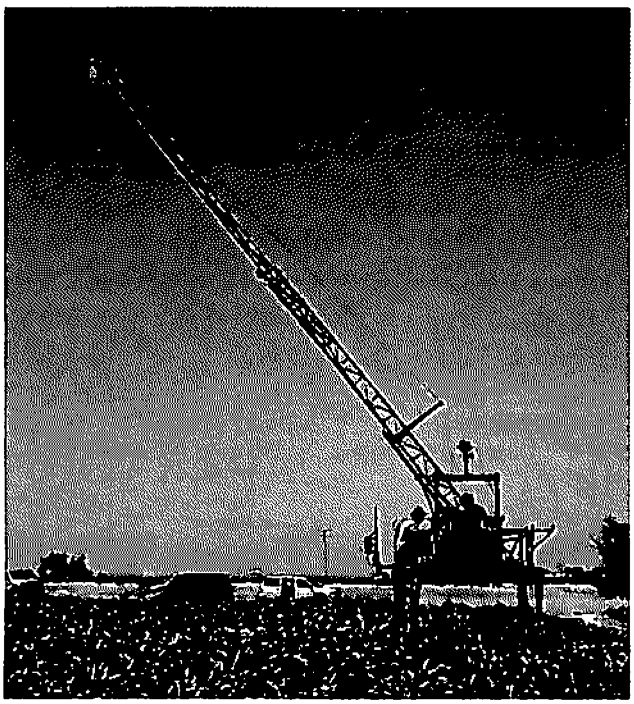

Figure 4. A boom-type data acquisition system mounted on a high-clearance tractor at the ARS Water Management Research Center in Ft. Collins, Colorado.

At the ARS location in Shafter, California, through a grant with NASA and in collaboration with industry (OKSI–Opto-Knowledge Systems, Inc., Torrance, California), a hyperspectral liquid crystal imaging system was mounted on a high-clearance vehicle for imaging plant spectral components from 450 to 1050 nm in narrow, 10-nm-wide wavebands. Images were calibrated using a $BaSO_4$ panel placed in the field of view of the camera before and after each acquisition. The objective was to measure important scene components for use in spectral unmixing of hyperspectral imagery collected with NASA AVIRIS imagery over the research site (Fitzgerald, 2001).

At the ARS U.S. Water Conservation Laboratory in Phoenix, Arizona, cotton experiments have been conducted using a linear-move irrigation system adapted to allow control of water and nitrogen applications over individual plots. The linear-move system also served as a remote sensing platform (named Agricultural Irrigation Imaging System, AgIIS, i.e., "Ag Eyes") (Figure 5). AgIIS uses a single downward looking sensor package that measures a 1-m-diameter area. As the sensor traveled along the length of the linear move, measurements were taken at 1-m intervals. A differentially corrected global positioning system (GPS) receiver was located at one end of the linear move, and processing algorithms were developed that assigned UTM coordinates to every sensor measurement. The linear move was operated at a speed so that sensor measurements could be gathered at approximately 1-m intervals in the direction of travel. Thus, when the data were displayed spatially, the "pixel" resolution was 1 by 1 m. The AgIIS sensor package was composed of four silicon detectors filtered to narrow

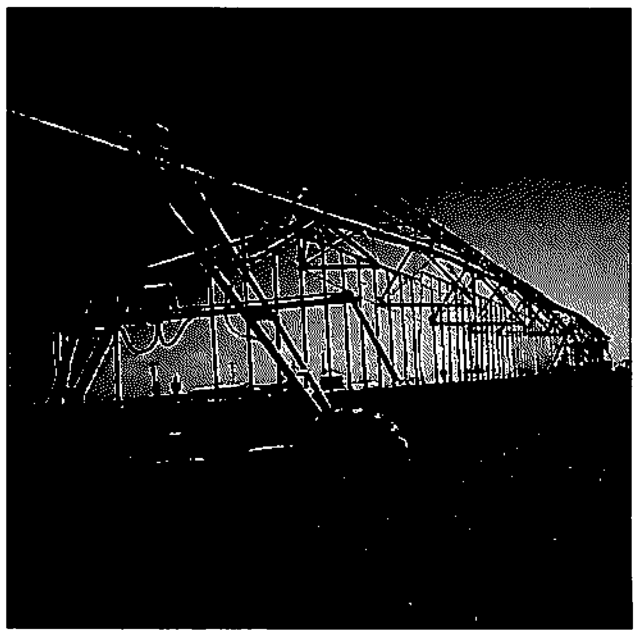

Figure 5. The linear move system serving as a platform for the Agricultural Irrigation Imaging System, AgIIS Ag Eyes, in Phoenix, Arizona.

wavelength intervals (~10 nm) in the red (670 nm), green (555 nm), red-edge (720 nm), and NIR (790 nm) portions of the spectrum, and an infrared thermometer. The reflective bands of AgIIS were calibrated to units of reflectance by taking the ratio of downward looking sensor mV readings to mV readings from an upward-looking sensor measuring the same spectral bands (Barnes *et al.*, 2000).

ARS scientists in Tucson, Arizona, are using a powered parachute as a sensor platform. The powered parachute is similar to an ultralight aircraft with a parachute for an airfoil (Figure 6). Regulations for take off and landing are minimal, and powered parachutes only require about 30 m for take off and landing. Permission from the landowner is all that is usually needed for a take-off site because the powered parachute can be transported on the back of a pickup. The main limitations to deployment of the powered parachute are that wind speeds must be less than 15 mph and ambient temperatures must be low enough to avoid thermal eddies. This platform has been used for ground reconnaissance in support of Landsat 7 satellite overpasses and the experimental Earth Observation 1 (EO-1) satellite at grassland and shrubland sites in southeastern Arizona. The payload is a hyperspectral radiometer (0.35 to 2.5 μm), a thermal infrared thermometer, and a GPS receiver connected to a single computer and keyboard. The advantages of this platform are that it can take off on a county road less than a mile from the research site and collect georeferenced data over several kilometers at minimal cost.

Cooperative Research and Development Agreement (CRADA) for Sensor Development

The largest CRADA in the history of the USDA ARS was developed to bring ARS scientists and private industry cooperators together to provide farmers with satellite-based information on the health of their crops. The CRADA partners were Resource21, LLC of Englewood Colorado; Boeing Company, Seattle Washington; Farmland Industries, Kansas City, Missouri; Agrium, Marconi Integrated Systems, Inc, San Diego, California; Institute for Technology Development (ITD), Inc, Ridgeland, Mississippi; and six ARS laboratories in Lincoln, Nebraska, Shafter, California, Phoenix and Tucson, Arizona, Ames, Iowa, Beltsville, Maryland, and Lubbock, Texas. Resource21 initiated the CRADA with plans to launch up to four satellites devoted to remote sensing for farmers. The role of Farmland Industries was to deliver the validated technology to its 600,000 farmer-members.

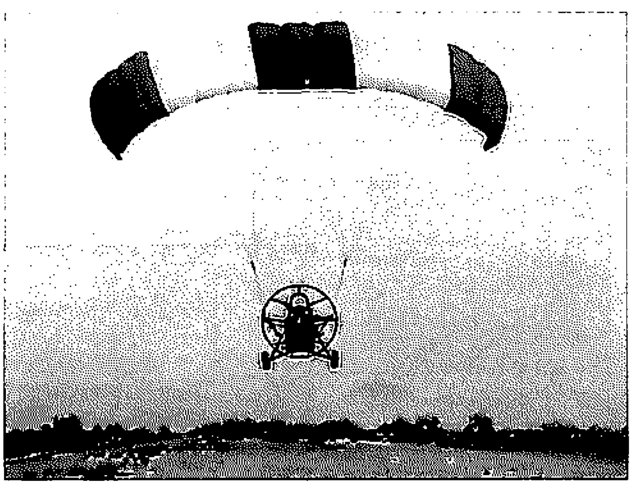

Figure 6. A powered parachute as a sensor platform in Tucson, Arizona.

The agreement specified that ARS scientists would set up nitrogen, weed, and drought-stress experiments and Resource21 would provide multispectral imagery over the well-instrumented ARS research plots throughout several seasons. This relation capitalized on the engineering expertise of the private industry cooperators, and the agronomic and agricultural remote sensing expertise of the ARS scientists. To represent field conditions, ARS researchers took detailed, systematic measurements of crop growth and development. Research results offered insights into sensor calibration and atmospheric correction (Moran *et al.*, 2001), correction for off-nadir viewing (Dymond *et al.*, 2001; Bryant *et al.*, 2003), crop and soil spatial variability (Bryant and Moran, 1999), yield limiting factors (Shanahan *et al.*, 2001), and nitrogen applications (Osborne *et al.*, 2001). The CRADA partners looked to ARS to help ensure the accuracy of the computer programs that produced the maps of crop and soil conditions and to make the industry research reliable and credible. ARS scientists helped the industry partners follow the proper research protocol to test their agricultural products and insure that results were valid and applicable to different regions of the country.

Other ARS CRADAs with private industry cooperators have had similar success. In a CRADA with Loral Corporation, ARS scientists in Phoenix were tasked with compiling a report on the "best" spectral wavelengths for agricultural management applications. Scientists at ARS Weslaco, Texas used a CRADA with the Institute for Technology Development (ITD) to develop an airborne hyperspectral imaging system (Yang *et al.*, 2001) and an interagency agreement with the Environmental Protection Agency (EPA) to design and assemble an aerial three-camera digital imaging system for monitoring and assessing environmental conditions of natural resources (Escobar *et al.*, 1997).

NASA Instrument and Science Teams

USDA scientists have been well represented on NASA science and instrument teams to provide advice to the U.S. Government concerning sensor specifications, data archives, operation, and the design of follow-on missions. ARS scientists have had such roles on the NASA Aqua Advanced Microwave Radiometer Team, the Japanese ADvanced Earth Observation Satellite II (ADEOS-II) Advanced Microwave Radiometer Team, NASA Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), NASA Landsat-7 Science Team, and NASA Earth Observation 1 (EO-1) Validation Team. This participation has resulted in sensor development with some attention to agricultural issues, such as operational atmospheric correction (Moran *et al.*, 2001), temperature retrieval from satellite measurements (Schmugge *et al.*, 2002b), selection of spectral wavebands suitable for monitoring natural resources (Nouvellon *et al.*, 2001), and use of microwave sensors over grassland regions (Jackson, 1997).

Radiometric Correction

Radiometric correction is defined here to include both calibration of radiometers and the atmospheric correction necessary to retrieve surface reflectance and temperature. Surface reflectance and temperature are comparable over time for monitoring seasonal crop and soil conditions and have become the basic quantities required for most agricultural algorithms and models.

Development of Laboratory Calibration Facilities

Similar to on-site sensor development, ARS calibration facilities were often developed when no facilities could meet the needs of agricultural applications. A good example is the IRT calibration facility in Phoenix, Arizona, at the ARS U.S. Water Conservation Laboratory (Figure 7). Calculation of a calibration equation for an IRT requires (1) the apparent temperature readout or output voltage from the sensor (T_{rel}), (2) the internal body temperature of the sensor (T_{body}), and (3) the true blackbody radiant temperature (T_{bb}) of the calibration target. The instruments are calibrated in a room that can maintain a steady ambient air temperature (±2°C) throughout each measurement session. A 15- by 15-cm extended area blackbody with a reported accuracy of 0.01°C is used as a calibration target.

The range of room temperatures used for calibration brackets the ambient temperatures experienced during field use. Blackbody temperatures are set from 0° to 70° at 5° intervals for each run. A full calibration will typically consist of 15 blackbody temperatures at each of ten room temperatures, resulting in 150 T_{rel}, T_{bb}, and T_{body} sets of measurements per instrument. Calibration coefficients are developed from the data using multiple linear regression techniques. A typical equation to calculate a corrected temperature, T_{corr}, would be the following: $T_{corr} = a_0 + a_1T_{rel} + a_2T_{body} + \dots$.

Development of Field Calibration Techniques

The measurement of radiation reflected from a surface must be accompanied by a near-simultaneous measurement of radiation reflected from a reference panel to calculate a bidirectional reflectance factor for the surface. Adequate calibration of the reference panel is necessary to assure valid estimates of reflectance. Thus, many ARS efforts have been directed toward calibration of reference panels for reflectance factor retrieval (RFR) from ground-based sensors, development of permanent, on-site reference panels for RFR from airborne sensors, and use of ARS field sites for sensor calibration and validation.

ARS scientists in Phoenix, Arizona, developed a procedure by which a reference panel can be calibrated with the sun as the irradiance source, with the component due to diffuse flux from the atmosphere subtracted from the total irradiance (Jackson *et al.*, 1987). Furthermore, the radiometer that is used for field measurements is also used as the calibration instrument. The reference panels are compared with a pressed polytetrafluouroethylene (halon) standard. The advantages of this procedure over conventional laboratory calibration methods are (1) the irradiance and viewing geometry is the same as is used in field measurements and (2) the needed equipment is available, or can be constructed, at most field research laboratories, including the press necessary to prepare the halon standard. The uncertainty of the method was estimated to be 1 percent, and this technique was used to provide a standard calibration of known accuracy for commercially available Spectralon panels (Jackson *et al.*, 1992). Moran *et al.* (2001) used the same approach to provide a standard calibration for chemically treated canvas tarps of large dimension (8 by 8 m) which could be deployed within the field of view of airborne digital sensors for RFR (Plate 1). They found that if tarps were deployed correctly and kept clean through careful use and periodic cleaning, and if tarp reflectance was determined through calibration equations that account for both solar and sensor view angles, the greatest sources of error were minimized. The major limitation of tarps as calibration sources was related to the difficulty associated with deploying heavy, cumbersome tarps under normal field conditions characterized by moderate wind, dust, heat, and possibly mud.

ARS scientists in Shafter, California, deployed a permanent panel of size 10 by 10 m, built from 2-cm-thick, 1.2- by 2.4-m plywood panels (Figure 8). Each was laid out with four rows of eight panels. The outer two rows were hinged so that they could be folded on top of the inner two rows when not in use. This prevented dust, rain, and ultraviolet (UV) solar radiation from changing the spectral characteristics of the panels. Each was painted with commercial exterior latex paint, and the paint was applied with a commercial sprayer to achieve an even coat. The three panels were painted varying shades of gray representing 0.05 to 0.07, 0.16 to 0.31, and 0.78 to 0.96 reflectance. The panels were repainted each year and, thus, surface reflectance varied. Reflectance values were measured using a spectroradiometer (400 to 1100 nm) several times during each season to quantify slight changes in the reflectance values due to dust, rain, or sun. Although minor, dust was probably the principal cause of changes in reflectance. The unpainted surfaces of the plywood panels were coated with sealant to protect them from water damage but despite this, the panels had to be replaced every two to three years.

Exploitation of ARS Field Sites for Sensor Calibration and Validation

Since the early 1980s, scientists have been conducting extensive, multi-disciplinary remote sensing experiments for sensor calibration and validation at well-instrumented ARS field sites. Four locations in particular have been emphasized: Walnut Gulch Experimental Watershed and the sur-

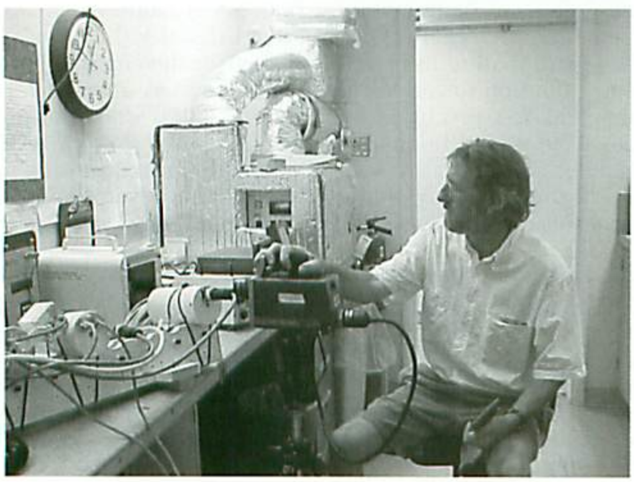

Figure 7. The infrared thermometer (IRT) calibration facility at the ARS U.S. Water Conservation Laboratory in Phoenix, Arizona.

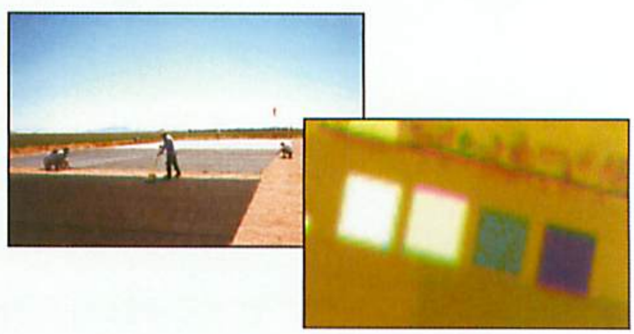

Plate 1. Chemically treated reference canvas tarps as seen from ground level (left) and as imaged from an airborne sensor (right).

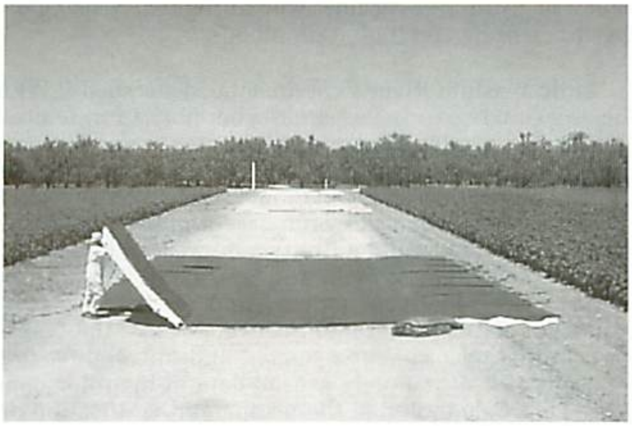

Figure 8. Permanent canvas and plywood reference targets deployed in Shafter, California.

rounding Upper San Pedro Basin (USPB), Maricopa Agricultural Center (MAC), Jornada Experimental Range, and the Little Washita River Experimental Watershed (LWREW). These sites and the ARS Beltsville Agricultural Research Center (BARC) in Beltsville, Maryland, have been designated as core EOS validation sites, resulting in multisensor aircraft and satellite overflights as part of the validation effort and to assess sensors for agricultural applications. Care has been taken to make the images and ground data from experiments at ARS sites available to the scientific community in databases such as the Water Conservation Laboratory Image and Ground Data Archive (WIGDA).

Walnut Gulch Experimental Watershed (WGEW) and Upper San Pedro Basin (USPB). The USPB in southeast Arizona has been the location of several hydrologic remote sensing experiments and encompasses the well-instrumented USDA ARS Walnut Gulch Experimental Watershed (WGEW) (Renard *et al.*, 1993) (Plate 2). At low elevations, the vegetation is mixed grass-brush rangeland typical of this region; at higher elevations, the region supports pinyon-juniper woodland and ponderosa pine forests. WGEW is operated by the ARS Southwest Watershed Research Center (SWRC) as part of a research program to conduct basic scientific research, develop new technology, and facilitate transfer of technology and research findings to other scientists, land managers, decision makers, and the public. The watershed is an outdoor laboratory to study hydrology, soil erosion, water quality, and climate change, and to evaluate the effects of land use and management on natural resources. The goal is to provide a permanent field facility in support of research to develop information for economically and

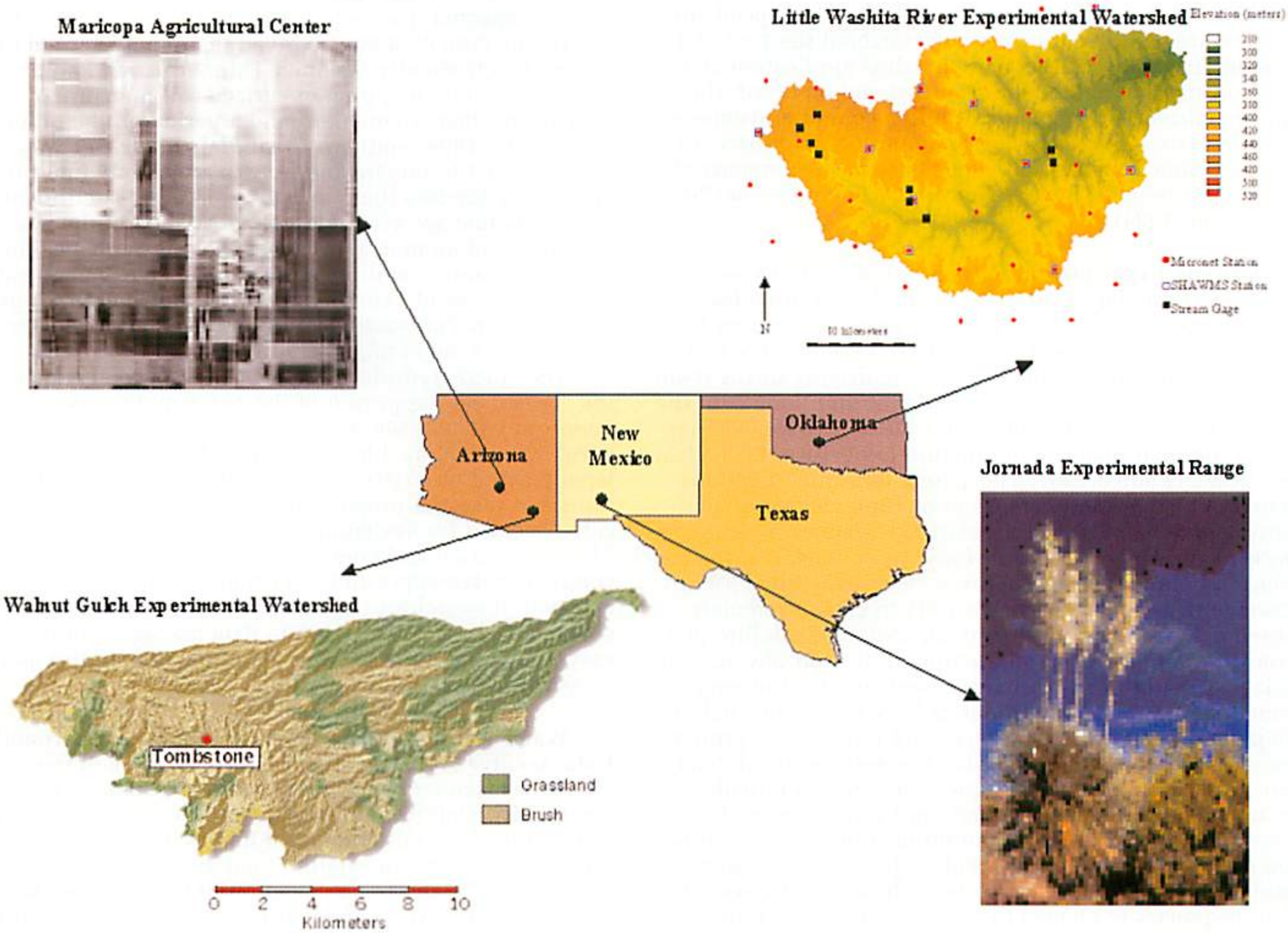

Plate 2. Location map for Maricopa Agricultural Center and Walnut Gulch Experimental Watershed in Arizona, Jornada Experimental Range in New Mexico, and Little Washita River Experimental Watershed in Oklahoma.

environmentally sustainable agriculture and natural resource management. The basic data acquired at WGEW is rainfall and runoff, water supply and quality, soil erosion, soil and vegetation status, and effects of management. The cooperators at WGEW include local ranchers and residents; consultants; city, county, state, and federal personnel; universities; and international organizations. The results of several multidisciplinary, intensive remote sensing experiments have been summarized in special issues of *Water Resources Research* (Kustas and Goodrich, 1994) and *Agricultural and Forest Meteorology* (Goodrich *et al.*, 2000).

Maricopa Agricultural Center (MAC). MAC has been the site of seven ARS multidisciplinary field experiments that focused on studies of multispectral remote sensing for evaluation of soil, plant, and atmospheric conditions (Jackson, 1990; Moran *et al.*, 1996). MAC, an 850-ha farm that is owned and operated by the University of Arizona, Tucson, Arizona, is located 48 km south of Phoenix, Arizona, and east of the town of Maricopa (Plate 2). MAC has two independently managed farms, the Demonstration farm and the Research farm, having 590 tillable ha and 174 ha, respectively. The mission of the Demonstration farm is to evaluate the cultural practices and technology that research has shown to have potential commercial application. The results of these efforts conducted on a commercial scale operation are then used to educate growers about the costs and possible benefits of implementing those practices. Near the center of MAC, there is an Arizona Meteorological (AZMET) station which provides hourly values of solar radiation, wind speed, air temperature, and vapor pressure throughout the year. All planting irrigation, tillage, and chemical application activities in every field at MAC are recorded and archived; these data are currently being entered into a computer database for web access. The results of many multidisciplinary, intensive remote sensing campaigns have been summarized in a special issue of *Remote Sensing of Environment* (Pinter and Moran, 1994).

Jornada Experimental Range. The Jornada Experimental Range (Jornada) in southern New Mexico provides a unique opportunity to use remote sensing techniques to study arid rangeland and responses of vegetation to changing hydrologic fluxes and atmospheric driving forces (Plate 2). Research by the USDA Forest Service and the ARS at the Jornada has been continuous since 1912. The Jornada has been a National Science Foundation Long-Term Ecological Research site since 1981. These long-term investigations have provided ground data on vegetation characteristics, ecosystem dynamics, and vegetation response to changing physical and biological conditions. To complement the programs of ground measurements, a campaign called JORNEX (JORNada EXperiment) began in 1995 to collect remotely sensed data from ground-based, aircraft, and satellite platforms to provide spatial and temporal data on physical and biological states of the Jornada rangeland. A wide range of ground, aircraft, and satellite data have been collected on the physical, vegetative, thermal, and radiometric properties of three ecosystems (grassland, grassland/shrub land transition, and shrub land) typical of both the Jornada, the northern Chihuahuan Desert, and southwestern U.S. deserts. Data from different platforms allowed the evaluation of the landscape at different scales. These measurements are being used to quantify hydrologic budgets and plant responses to change in components in the water and energy balance at the Jornada. JORNEX campaigns are mounted twice each year to coincide with the ends of the dry and rainy seasons, and to date, 13 field campaigns have been completed. A description of the unique Jornada arid land location for experiments to validate satellite systems was given in a special issue of *Remote Sensing of Environment* by Havstad *et al.* (2000).

Little Washita River Experimental Watershed (LWREW). The ARS Grazinglands Research Laboratory in El Reno, Oklahoma, operates a fully instrumented watershed on the Little Washita river covering an area of 611 km^2 located southwest of Chickasha, Oklahoma (Plate 2). The hydrology, soils, and climate research based on the LWREW has attracted state, federal, and university researchers for several large field studies, including Washita'92, Washita'94, Southern Great Plains'97 (SGP97), and SGP99. Washita'92 was a cooperative experiment between NASA, the USDA, several other government agencies, and universities to test the usefulness of remotely sensed data in hydrologic modeling. The goals included the testing and verification of several new remote sensing devices and the development of databases for target-sensor interaction algorithms. The primary objective of Washita'94 was to provide combined ground and remotely sensed data sets for modeling and analysis of hydrologic state and flux variables. The determining factors in the timing of this field campaign were the Space Shuttle Imaging radar missions (SIR-C) in April and August of 1994. The Southern Great Plains 1997 (SGP97) Hydrology Experiment was a collaborative effort to establish that the retrieval algorithms for surface soil moisture developed at higher spatial resolution using truck- and aircraft-based sensors can be extended to the coarser resolutions expected from satellite platforms (Jackson *et al.*, 1999). The core of SGP97 involved the deployment of the L-band Electronically Scanned Thinned Array Radiometer (ESTAR) for daily mapping of surface soil moisture over an area greater than 10,000 km^2 and a period on the order of a month. The 1999 Southern Great Plains (SGP99) Experiment was designed to understand how to effectively interpret and utilize the less than optimal sources of satellite microwave data that are available now or will be in the near future and explore new approaches that may enhance the ability to measure soil moisture from space. Some results from this series of experiments were published in a special issue of *IEEE Transactions on Geoscience and Remote Sensing* (Jackson *et al.*, 2001).

The SGP97 Hydrology Experiment is a good example of the "brown bag" approach of the ARS remote sensing experiments at WGEW, USPB, MAC, Jornada, and LWREW. That is, SGP97 was developed by a team of interested scientists largely based on existing sponsored scientific investigations and research projects; no science teams were specifically selected for designing and executing the experiment. The cooperation and contributions by many resulted in a comprehensive opportunity for multidisciplinary scientific research. Research use of the experimental data was encouraged and care was given to data management to allow easy access upon the completion of quality control and cross calibration and validation.

Water Conservation Laboratory Image and Ground Data Archive (WIGDA). WIGDA is an example of the ARS efforts to make remote sensing data accessible to a larger community. Continuing work at MAC, WGEW, and USPB has resulted in the accumulation of hundreds of spectral image files from a variety of satellite- and aircraft-based sensors (the "images"), and the association of those images with data files containing high-quality ground-based measurements of soil, plant, and atmospheric conditions (the "ground data"). These images and the supporting ground data have been compiled in one location, and transferred in an orderly fashion to compact disks (CD ROM). Each image on CD ROM includes a companion "readme" file containing metadata on the acquisition data and location, processing level, file size and format, and any relevant comments about the image or the archiving procedure. Supporting files of ground, atmospheric, and low-altitude aircraft measurements were archived with an internal header describing techniques, instrumentation, location, and other relevant information. Metadata on all archived images and ground data were entered into a database to link the information in the two data sets and to enable easy queries of either image or supporting ground data files (Moran *et al.*, 2000b).

Sensor Development Direction

The direction of sensor development and radiometric correction for agricultural application is being driven largely by agricultural remote sensing research. These trends (addressed in the other papers in this special issue) translate into a variety of potential sensors that include integrated sensors for multispectral data fusion of visible, NIR, SWIR, TIR, and radar; sensor systems combining GPS, GIS, remote sensing, and variable rate (VR) chemical applicators; sensor standardization for agricultural applications; and investigation of new sensor technologies to support agricultural research.

Integrated Sensors

The satellite-based sensors currently in orbit or planned for the next ten years offer restricted wavelength coverage that limits data fusion (Moran *et al.*, 1997). Studies have found that combinations of different remote sensors can increase the available information and allow applications that could not otherwise be possible. Research based on combined analysis of visible, NIR, and TIR measurements has shown the synergistic value of reflective and thermal data to monitor surface energy and water fluxes (e.g., Kustas and Norman, 1996). Combining surface reflectance and radar backscatter allowed discrimination of surface soil moisture content over a heterogeneous, semiarid region in Arizona (Plate 3; Moran *et al.*, 2000a). Daughtry *et al.* (1995) used a combination of visible, NIR, and SWIR reflectance measurements to develop a cellulose absorption index (CAI) that discriminates plant residues from soils. The CAI algorithm is also well suited for local and regional surveys of conservation practices and could be implemented using existing and future aircraft- and/or satellite-borne sensors. These are only a few examples of the applications that may be possible with deployment of integrated sensor systems.

Another trend is the use of integrated systems to combine the technology of GPS, GIS, remote sensing, and variable rate chemical applicators. For example, Hanson *et al.* (1995) described a herbicide application system mounted on a tractor with a GPS guidance system which was linked to a digital weed map, allowing only weed infested areas of the field to be sprayed. Similarly, USDA ARS scientists in Lincoln, Nebraska, have developed a mobile chlorophyll meter to help farmers decide if their corn crop needs more N fertilizer employing fertigation or high-clearance sprayer. This integrated sensor system networks 31 four-band sensors with a GPS system to collect data to calculate spectral indices, such as Normalized Difference Vegetation Index (NDVI), and then make spatial N fertilizer need maps. These sensors are commercially available to research groups on a limited basis.

Sensor Standardization

Many agricultural applications of remote sensing require a temporal series of measurements, and thus, sensor standardization is crucial. For example, the focus of much of the work in precision agriculture is to define "management units" of relatively uniform soil qualities that determine productivity. Studies have shown that such units can be defined by remotely sensed images acquired annually over a period of five to seven years (Yang and Anderson, 1996). In studies dependent on temporal measurements, it is imperative that the sensor provide standard information over time so that crop and soil variations are not confused with changes in sensor configuration or deployment. Despite this compelling argument, there are still few opportunities to compile a longterm image set with a standardized, calibrated sensor. The exception is the data set provided by the Landsat series of Thematic Mapper (TM) sensors. Landsat-4 and -5 TM and Landsat-7 Enhanced TM Plus (ETM+) sensors were designed with near-identical technology and could provide an uninterrupted stream of TM and ETM+ images to a potential span of 32 years.

A laudable effort has been made by NASA through the Landsat Data Continuity Mission (LDCM) to extend this image stream. The Earth Observation (EO-1) satellite was launched in 2001 as a technology validation mission with sensors that could update Landsat ETM+ technology while maintaining data geometric and radiometric continuity. The EO-1 Advanced Land Imager (ALI) has sensor characteristics patterned after ETM+, and EO-1 is currently orbiting to match the Landsat-7 orbit within one minute. The critical differences between ALI and ETM+ are related to spectral response functions (ALI spectral bands differ from ETM+ spectral bands in the blue, NIR, and SWIR wavelengths) and sensor technology (ALI was designed to demonstrate the advanced capability of new technologies, including a push-broom detector configuration and an innovative radiometric calibration approach). ARS scientists in Tucson have been funded by NASA to assess both the quality of ALI data, and the ability of ALI-derived data products to meet the needs of the Landsat user community for agricultural and hydrologic research.

New Sensor Technologies

New sensor technologies are being investigated in response to agricultural research. Some of these include natural and genetically induced fluorescence, soil electrical conductivity, lidar, hyperspectral, and multiband thermal. Example applications of each are given below.

Flourescence

Chappelle *et al.* (1995) demonstrated that crop residues fluoresce when illuminated with ultraviolet radiation, while most soils do not fluoresce. This innovative application of fluorescence techniques led to a U.S. patent application and a series of prototype instruments designed to meet the needs of the NRCS for measuring crop residue cover. This research will be extremely significant because hand-held versions of the fluorescence instruments could become the final arbitrator for the NRCS in contested decisions on the adequacy of crop residue cover in important conservation programs.

Ongoing research in the Plant Stress and Germplasm Development Research unit at Lubbock, Texas is targeting the development of plant stress reporting systems. Transgenic plants engineered to self-report several abiotic stresses will be generated, providing the potential for remote detection of plant stress levels. At present, the best developed reporter systems that allow nondestructive remote monitoring are the firefly luciferase and the green flourescent protein (GFP) from jellyfish. GFP has the advantage of requiring no other cofactor than molecular oxygen for signal generation. Three stress responsive promoter genes are currently available. These are highly inducible, stress specific, and active in both roots and leaves, allowing assays in both pigmented and non-pigmented tissue. These promoters are responsive to heat shock

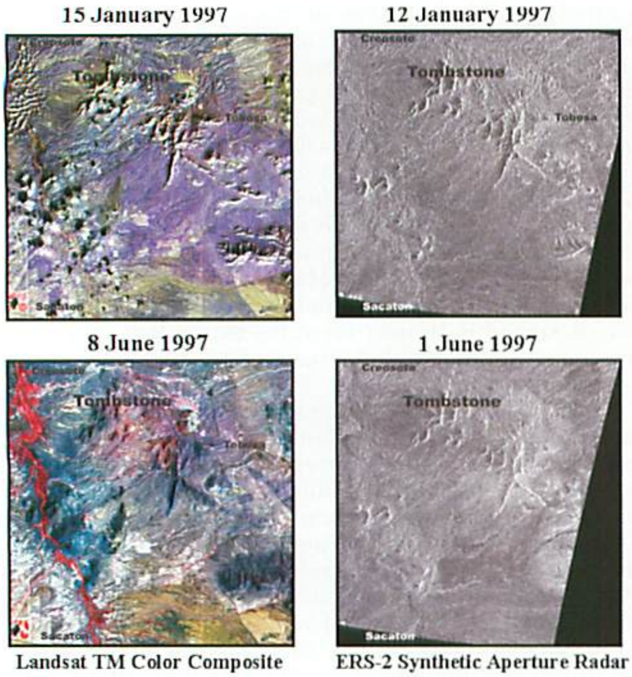

Plate 3. Near-coincident Landsat color composite and ERS-2 SAR scenes near Tombstone, Arizona.

thermal stress, water deficit, cold and salt stress, and phosphorus starvation. With the availability of these self reporting transgenics, sensors designed to detect and quantify flourescence in specific wavelengths will be required.

Bulk Soil Electrical Conductivity
Researchers at the George E. Brown, Jr. Salinity Laboratory in Riverside, California pioneered the use of bulk soil electrical conductivity (ECa) measurements in agriculture. Early research investigated the use of electrode-based ECa measurements as an estimate of salinity (Rhoades and Ingvalson, 1971). Continued research led to the production of the first commercial ECa sensor, the EM38 from Geonics Ltd. of Mississauga, Ontario, Canada (Rhoades and Corwin, 1981). With the advent of GPS technology, ARS researchers have developed systems to mobilize the EM38 and synchronize its output with GPS positioning data for efficient mapping of ECa (Jaynes *et al.*, 1993; Sudduth *et al.*, 2001). A mobile version of the electrode-based sensor was also developed at the Salinity Laboratory (Carter *et al.*, 1993). The electrode-based approach was further refined into a commercial product by Veris Technologies of Salina, Kansas.

Soil properties that influence ECa include soil salinity, clay content, and cation exchange capacity, clay mineralogy, soil pore size and distribution, soil moisture content, and temperature. Soil ECa measurements can be used to provide indirect measures of these properties if the contributions of the other affecting soil properties to the ECa measurement are known or can be estimated. In some situations, the contribution of within-field changes in one factor will be large enough with respect to variation in the other factors such that ECa can be calibrated as a direct measurement of that dominant factor. At the Salinity Laboratory, Lesch *et al.* (1995a; 1995b) used this direct calibration approach to quantify within-field variations in soil salinity under uniform management and where water content, bulk density, and other soil properties were "reasonably homogeneous." Direct calibrations have been obtained for the depth of topsoil above a subsoil claypan horizon by ARS researchers in Missouri (Doolittle *et al.*, 1994; Kitchen *et al.*, 1999) and for herbicide partition coefficients in Iowa (Jaynes *et al.*, 1995). Because soil ECa integrates texture and moisture availability, two spatially variable characteristics that affect crop productivity, ARS scientists have also used ECa sensing to help interpret variations in grain yield maps (e.g., Jaynes *et al.*, 1993; Sudduth *et al.*, 1995; Kitchen *et al.*, 1999).

LIght Detection and Ranging (Lidar)
Lidar systems measure the delay in the return signal from very short pulses of transmitted coherent light. Profiling and scanning lidar systems can provide accurate measurements of relative surface height at high resolutions. This technology has been used to monitor the dramatic displacement of native grasslands with shrublands in southwestern rangelands and ultimately quantify the impact on grazing land for domestic livestock. Rango *et al.* (2000) used active scanning lidar to provide accurate estimates of the shapes and areal distribution of dune and interdune areas in New Mexico (Plate 4). The use of scanning lidar

Plate 4. Scanning lidar for mapping rangeland topography, dune distribution, and vegetation cover in New Mexico.

systems together with optical multispectral data provided information that could not be easily obtained using other surveying methods.

Hyperspectral

Unlike multispectral remote sensing where a few wavebands are recorded, hyperspectral systems record energy in dozens or hundreds of contiguous narrow wavebands, typically from 400 nm up to 2500 nm. Techniques such as principal components analysis, spectral unmixing, and neural networks are being applied to these data sets to isolate unique features in the data sets. Spectral unmixing is especially intriguing because it can produce abundance maps indicating, pixel by pixel, the relative quantity of each scene component in a pixel. For example, relative percent cover by healthy canopy, pest damaged canopy, and soil type can be estimated (Fitzgerald, 2001).

ARS investigators in Beltsville, Maryland were participants on a NASA Small Business Incentive Research (SBIR) program with a commercial remote sensing firm to develop a lightweight visible, NIR hyperspectral sensor and its associated data processing algorithms (Walthall *et al.*, 1999). A primary emphasis of the ARS participation was assuring that radiometric and geometric calibration suitable for precision farming applications were integrated into the system. The investigators' research fields were periodically flown as part of the system development. The emphasis on calibration has resulted in a system that appears to provide solutions to many common problems associated with the acquisition of high quality, calibrated hyperspectral data with a 24- to 48-hour turnaround time. The remote sensing firm now has several agricultural customers and is presently working on the development of a sensor that extends spectral coverage to the shortwave infrared.

Multiband Thermal

The separation of temperature and emissivity effects in the observed thermal infrared ($7 \leq \lambda \leq 14$ μm) is difficult without ancillary information. With multispectral TIR observations, it is possible to make this separation (Gillespie *et al.*, 1998), as has been demonstrated by ARS scientists with data from both aircraft (e.g., Thermal Infrared Multispectral Scanner, TIMS; Schmugge *et al.*, 2002b) and satellite (ASTER; Schmugge *et al.*, 2002a) platforms. Emissivity is a fundamental property of the Earth's surface, and at present its spectral, spatial, and temporal variations are not well known. The objective of these multispectral systems is to acquire improved soil surface composition determination through the spectral emissivity observations, and with these emissivity data to obtain surface temperatures. While hyperspectral TIR data would be desirable for achieving these objectives, they are not available to any significant extent and we will have to work with the five bands of the ASTER instrument (Yamaguchi *et al.*, 1998) in the 8- to 12-μm portion of the spectrum.

The range of minerals found in exposed soils is usually quite limited, particularly with older, more developed soils, in which iron oxides, quartz, and clays dominate. The mineral content of soils can be analyzed remotely, based on their spectral properties: e.g., iron oxides produce absorption features in the visible and NIR (Landsat), and clays and carbonates in the SWIR (Landsat), while quartz has characteristic features only in the TIR. Soils are often vertically stratified, and these compositional changes provide a way to measure soil erosion remotely. For example, buried calcium carbonate horizons are common in deserts, but are only exposed by erosion.

More generally, visible, and NIR reflectance and TIR emissivity are complementary parameters that are sensitive to different absorption processes, which together can be used to describe the chemical composition of the Earth's surface, and the abundance of vegetation. The complementarity arises because vegetation and some minerals are most distinctive in the solar reflectance region whereas major rock-forming minerals (silicates) are most distinctive in thermal emissivity.

Challenges and Future Interactions

Though a great deal of progress has been made in sensor development and radiometric correction that applies to agricultural remote sensing, there are still challenges to be faced. First, there is no general agreement on critical spectral regions for agriculture and the sensor specifications for a dedicated, orbiting agricultural sensor. Moran (2000) offered a template for determining priorities in system design and technology development. A four-step procedure was demonstrated (1) to prioritize user information requirements, (2) to assess the ability of remote sensing science to meet such requirements, (3) to translate information requirements into system specifications, and (4) to assess the ability of current technology to fulfill system specifications. A dedicated effort to implement this procedure could lead to standardization of sensors, filters, and RFR algorithms and standardization of sensor calibration and deployment.

Second, advances in radiometric correction have been focused primarily on on-board radiometric reference sources, such as lamps and solar-illuminated diffuser panels. However, calibration of radiometers is only the first step in providing the surface reflectance and temperature products required by agricultural models and algorithms. The next steps include cloud screening, atmospheric correction, correcting for differences in sensor viewing angle and field of view, and accounting for mixed pixels due to coarse spatial resolution. Strides have been made to provide operational approaches for many of these (see review by Moran *et al.* (1997)), but still there is no standard, accepted procedure for operational reflectance and temperature retrieval.

Finally, there are difficulties resulting from lack of communication between and education of all involved parties. Whether image-based remote sensing technology is included in emerging agricultural systems will depend on the ability of commercial image providers, engineers, and research scientists to meet the stringent requirements for agricultural information products. A strategy will have to be developed for independent validation of algorithms produced by research scientists and proprietary products produced by for-profit commercial companies to satisfy the requirements of risk-adverse resource managers. Efforts should be focused on a systematic, triangular education of image providers, research scientists, and users through inclusion of all clients in program development and implementation.

Within the ARS, the continuum of research could be enhanced through facilitation of lending and borrowing sensors, development of a network of large permanent calibration targets at ARS locations, and nurturing a common vision of ARS field sites as long-term outdoor laboratories for sensor development and radiometric correction. While NASA and, more recently, commercial remote sensing firms are focused on advancing sensor technologies, ARS has a very strong role in investigating and optimizing sensor applications, sensor calibration, and ultimately sensor packaging for agricultural applications. To promote research in the use of high-cost, new technologies, the USDA and ARS should make a commitment to large-ticket items to encourage state-of-the-art research.

In a time of shrinking resources, ARS locations throughout the United States should pool resources to support large scale field experiments and facilitate multi-site evaluations of post-processing algorithms. A highly valuable ARS-wide effort would be determination and subsequent implementation of ARS-wide standards for sensor development, calibration, and deployment. Finally, the USDA should follow the example of other federal agencies and fund interagency agreements to achieve common goals.

For its part, the USDA, and especially the ARS, will have to take a proactive role as a voice for the promotion of sound remote sensing principles for agriculture. The continuum of remote sensing research conducted by the ARS that ranges from basic remote sensing science to the development and testing of technologies suitable for almost immediate commercialization assures that remote sensing will be able to address the information needs of agriculture. Publication of research results in conference proceedings and peer-reviewed journals, and as monographs or handbooks containing recommended procedures, will continue to emphasize the importance of sensor development and calibration demanded by agricultural applications.

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